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Beach erosion downcoast of Pengambengan fishing port in western part of Bali Island

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Abstract

Beach changes near Pengambengan fishing port in the western part of Bali Island, Indonesia, were investigated by the analysis of satellite images and field observations. In this area, northwestward longshore sand transport prevails because of the oblique wave incidence from the Indian Ocean, and this longshore sand transport has been blocked by a fishing port breakwater, resulting in severe downcoast erosion. As a measure, a seawall has been constructed, instead of maintaining the continuity of the natural longshore sand transport. The adoption of this method caused further downcoast erosion. The sand bypassing method should be adopted to mitigate such erosion.

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Keywords: *Bali Island; Bali Strait; longshore sand transport; downcoast erosion; seawall; sand bypassing*

1. Introduction

In general, longshore sand transport prevails on coasts located near the wave-shelter zone behind an offshore island or in a strait, because waves are obliquely incident at a large angle in the direction normal to the shoreline. When a structure, such as a port breakwater, is extended on these coasts, continuous longshore sand transport is blocked, resulting in erosion downcoast of the structure with accretion upcoast. As another case, when waves are obliquely incident at an angle larger than 45° in the direction normal to the coastline, a small perturbation on the

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shoreline may develop into sand spits with rhythmic shapes because of shoreline instability. Ashton et al. (2001) succeeded in the reproduction of these topographic changes using a numerical model based on a longshore sand transport formula of the one-line model. Ashton and Murray (2006) called this phenomenon the high-angle wave instability. Recently, Serizawa et al. (2012) have shown that sand spits and cuspate forelands with rhythmic shapes in the Azov Sea, described by Zenkovich (1967), could be numerically reproduced using the BG model (a three-dimensional model for predicting beach changes based on Bagnold's concept) (Serizawa and Uda, 2011).

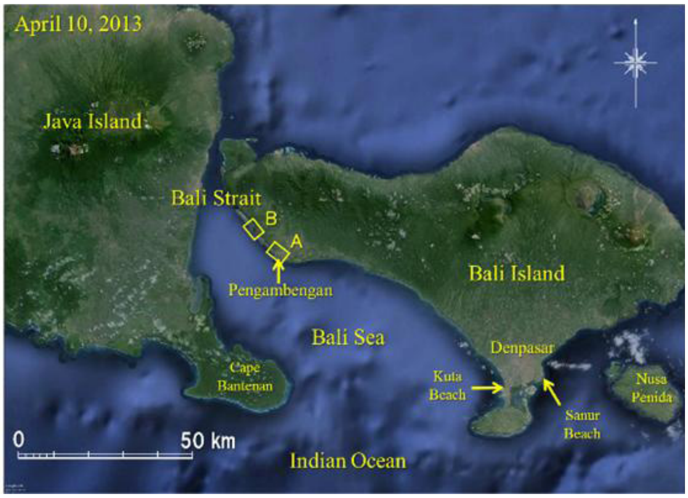

Fig. 1. Satellite image of Bali Island.

The west end of Bali Island in Indonesia is located immediately east of Java Island, and separated by the Bali Strait with a 2.3 km width. In the entrance to Bali Strait, northwestward longshore sand transport prevails, because waves incident from the Indian Ocean propagate parallel to the mean direction of the coastline. At Pengambengan close to the entrance of the strait, a fishing port breakwater was constructed in 2000, and typical beach changes when predominant longshore sand transport was blocked by the breakwater were observed (Uda et al., 2004). Instead of the adoption of the sand bypassing method to guarantee continuous sand movement, a seawall has been constructed along the downcoast as a measure against beach erosion, similarly to the case in Japan, resulting in the further expansion of the eroded area. On the other hand, north of this fishing port, a long sand bar has developed owing to shoreline instability, and sand transported by longshore sand transport has been deposited at the tip of the sand spit, which resulted in the disruption of continuous sand supply downcoast, causing further downcoast erosion. In this study, these two problems were selected, and site observations were carried out. Then, the present case was compared with the beach changes at Santa Barbara in California and Oyashirazu fishing port in Niigata Prefecture, Japan, and we argued that sand bypassing should be adopted as a measure, instead of constructing a seawall downcoast of the fishing port.

2. Geographical features of study area

The west end of Bali Island is separated from Java Island by the Bali Strait at the narrowest width of 2.3 km, as shown in Fig. 1. The smoothly curved concave coastline runs between Kuta Beach, one of the famous beaches located on Bali Island, and Pengambengan, 72 km northwest of Kuta Beach. However, west of Pengambengan, the distance to the opposite shore is markedly narrowed as it is the narrowest point of the funnel-shaped Bali Strait. Because the south coast of Bali Island faces the Indian Ocean, wave incidence from the south predominates (San-nami et al., 2013). Furthermore, because Cape Bantenan extends at the southeast end of Java Island and effectively shelters wave incidence from the south, northwestward wave incidence prevails in the channel area west of Pengambengan. This wave direction is approximately equal to the coastline orientation west of Pengambengan, implying the predominance of northwestward longshore sand transport on coasts west of Pengambengan.

Site observations were carried out on November 24, 2011 in rectangular area A, which includes Pengambengan fishing port, and area B, where the coastline orientation markedly changes, as shown in Fig. 1. Figure 2 shows the satellite image taken on July 9, 2009 and the location numbers of the site photographs taken in area A. The construction of Pengambengan fishing port started in 2000 (Uda et al., 2004). A semicircular breakwater was extended on the south side of the fishing port with an opening of 220 m length to the north breakwater, as shown in Fig. 2. The length of the south breakwater is 660 m. Because predominant waves are incident from the southeast approximately parallel to the mean coastline in this area, northwestward longshore sand transport prevails, resulting in accretion south of the breakwater. In contrast, the beach has been eroded north of the fishing port, and the coastline was completely covered with the seawall. Although the shoreline connected to the south breakwater at site No. 1 on July 9, 2009, sand was transported westward along the south breakwater and deposited inside the fishing port, and a sand spit elongated to block the navigation channel, as shown in Fig. 3, up to May 12, 2011. This explains the disruption of northward longshore sand transport at this fishing port. Figure 4 shows the satellite image taken on May 30, 2014. A jetty was extended at the entrance of the fishing port to block the successive deposition of sand inside the port, and sand has already been deposited on the south side of the jetty.

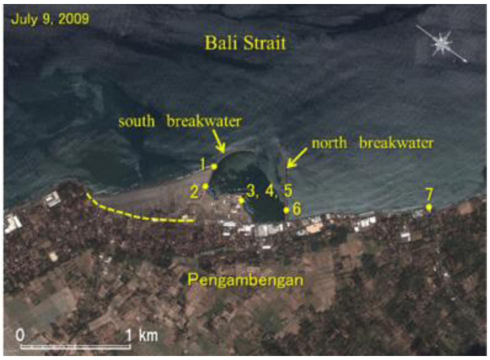

Fig. 2. Satellite image of Pengambengan fishing port taken on July 9, 2009.

Fig. 3. Satellite image of Pengambengan fishing port taken on May 12, 2011.

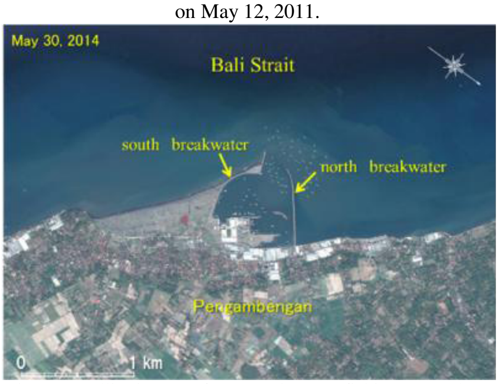

Fig. 4. Satellite image of Pengambengan fishing port taken on May 30, 2014.

Further north of Pengambengan fishing port, waves are obliquely incident at a large angle in the direction normal to the shoreline, because the predominant direction of incident waves is approximately parallel to the mean direction of the coastline. Therefore, the infinitesimal perturbation on the shoreline can develop to form sand spits with rhythmic forms owing to the shoreline instability, as described in previous papers (Zenkovich, 1967; Ashton and Murray, 2006; Serizawa et al., 2012). In particular, the coastline significantly protrudes 6.6 km northwest of the fishing port, and a sand bar of 2 km length extended northward parallel to the coastline from the tip of the protrusion, as shown in Fig. 5, and the tip of the sand bar approached a mere 128 m from the opposite shore on July 9, 2009. Because the tip of the slender sand bar did not connect to the opposite shore at this stage, sand supplied by northward longshore sand transport was used only for the elongation of the sand spit without sand supply to the downcoast, implying that the beach was eroded near the shoreline on the opposite shore. The second observation site is the eroded beach downcoast of this elongating sand bar. The location numbers of site photographs taken downcoast of the slender sand bar are shown in Fig. 5. The observation site is located on the concave shoreline north of the slender sand bar. Figure 6 shows the slender sand bar deformation up to May 30, 2014, and the sand bar elongated with the attachment of the tip to the opposite shore, whereas the sand bar was eroded upcoast and a discontinuous shoreline was formed with an opening of 590 m with the elongation of another sand spit in front of the river mouth. A sandy beach was recovered downcoast where it was once eroded.

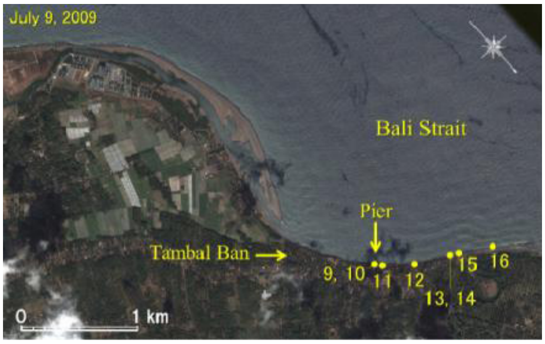

Fig. 5. Elongated sand bar along shoreline taken on July 9, 2009.

Fig. 6. Elongated sand bar along shoreline taken on May 30, 2014.

3. Beach changes due to obstruction of longshore sand transport by fishing port breakwater

3.1. Sand deposition upcoast of Pengambengan fishing port

Photo 1 shows the shoreline upcoast of the fishing port extending to the headland, as shown in Fig. 2, taken from the top of the south breakwater, while facing the southeast. A sandy beach, composed of fine and medium-size sand with a gentle slope, continuously extended to the headland south of the fishing port. The berm height was approximately 1.2 m near the breakwater. Photo 2 shows the unloading area inside the south breakwater, built using boulders, facing the tip of the south breakwater. A number of fishing boats were moored inside the port, and Photo 3 shows the unloading area where a gentle concrete slope was constructed, and many people were actively working to unload fishes from fishing boats, as shown in Photos 3, 4 and 5. Although the mechanization level for the manpower-dependent fuel loading of the fishing boats or the unloading of fishes was low compared with the situation in Japan, many people actively worked, which is reminscent of the past scenery of fishing ports in Japan. Thus, Pengambengan fishing port has really been utilized as a fishing port and as a base of unloading fishes in this area.


Photo 1. Southeast view from south breakwater of Pengambengan fishing port.


Photo 2. Unloading area inside of Pengambengan fishing port.


Photo 3. Concrete slope for unloading of fishes.


Photo 4. Unloading of caught fishes by a pair of fishermen.


Photo 5. Many fishing boats moored inside the fishing port.

3.2. Beach erosion downcoast of Pengambengan fishing port

The beach had already been eroded north of the fishing port owing to to the blockage of northward longshore sand transport by the fishing port breakwater (Uda et al., 2004). Photo 6 shows the eroded beach downcoast of the fishing port, taken from the base of the north breakwater, as shown in Fig. 2. The coastline was completely covered with the concrete seawall with no foreshore in front of the seawall. At site No. 7 located 1.3 km northwest of the north breakwater, the seawall collapsed owing to severe beach erosion, and the debris of the destroyed seawall extended straight under the sea surface, as shown in Photo 7. Moreover, at site No. 8 located 1 km north of site No. 7, although a natural sandy beach with tropical vegetation, such as palm trees, inland remained, as shown in Photo 8, the beach has been severely eroded, and many roots of palm trees were left on the shoreline, which is evidence of successive shoreline recession. Furthermore, behind the shoreline, a scarp was formed in front of houses and coastal vegetation died out while forming lumps of earth.

Photo 6. Coastline protected by seawall north of fishing port.

Photo 7. Collapsed seawall due to erosion north of fishing port.

Photo 8. Scarp erosion of natural coast 1.0 km north of site No. 7.

4. Beach erosion downcoast of a slender sand bar

Downcoast of the slender sand bar, the beach has been severely eroded, and wooden fences have been constructed as a measure against beach erosion. Photo 9 shows the beach condition immediately downcoast of the pier, as shown by an arrow in Fig. 5. Wooden fences have been continuously constructed in this area as a measure against erosion, as shown in Photo 10, facing northwest on top of the pier. Two rows of wooden fences have been constructed with gravel in between to prevent further beach erosion. However, part of these wooden fences collapsed owing to the wave action. Photo 11 shows the eroded coastline looking towards the pier from site No. 11. As a result of the severe erosion, isolated roots of palm trees were observed. Further downcoast, a seawall made of circular concrete piles extended, as shown in Photo 12. However, on the downdrift side of the seawall, land was eroded up to the asphalt road, forming a scarp despite the installation of wooden fences, as shown in Photo 13. Photo 14 shows the northwest end of the wooden fence, and the entire coastal road was eroded, forming a scarp of 2 m height, and sand bags were placed as an urgent measure. Also, a tree isolated by the successive erosion can be seen. Photo 15 shows the two rows of wooden fences to protect houses against erosion on the north side, but they seemed to be ineffective. However, at site No. 16 located at the north end of the study area, a river that meandered in the northwest flows into the sea with the development of a large river mouth bar, and thus a wide foreshore was left showing accretion, as shown in Photo 16. Thus, beach erosion ceased at the river mouth 1.5 km northwest of the tip of the large-scale sand spit.

Photo 9. Pier extended at a location shown by an arrow in Fig. 5.

Photo 10. Northwest view from top of pier. Owing to the downcoast erosion, a number of wooden fences were constructed.

Photo 11. View of the pier from downcoast location.

Photo 12. Seawall made of concrete piles.

Photo 13. Eroded road that was protected against beach erosion by many wooden fences.

Photo 14. Scarp of 2 m height formed at northwest end of wooden fences.

Photo 15. Two rows of wooden fences protecting houses.

Photo 16. Large amount of sand deposited at river mouth.

5. Discussion

The same phenomena as observed around the Pengambengan fishing port, namely, sand deposition and erosion upcoast and downcoast of the breakwater, respectively, had occurred at Santa Barbara in California in the United States after the extension of the port breakwater, which was first studied by R. L. Wiegel, prompting various measures to be taken. The shoreline changes after the construction of the port breakwater at Santa Barbara are shown in Figs. 9-3 and 9-4 (p. 380) in the paper by Komar (1998). Komar described that eastward longshore sand transport of 2.15×10^5 m^3/yr was blocked by the breakwater and a wide foreshore was formed west of the breakwater, whereas a sand spit was formed by the successive deposition of sand turning around the tip of the breakwater inside the port. The construction of the straight offshore breakwater at Santa Barbara began in 1927, and then the offshore breakwater was connected to the land by 1930. Since then, sand bypassing has been carried out, in which sand dredged from the navigation channel inside the port was transported downcoast of the breakwater.

Figure 7 shows the satellite image of Santa Barbara taken on April 19, 2013. Sand bypassing is sufficiently effective that a sandy beach is maintained east of the port at present. The elongation of the sand spit is very similar to that at Pengambengan fishing port seen in the satellite image taken on May 12, 2011. Although 86 years have

Fig. 7. Satellite image of Santa Barbara, California.

Fig. 8. Satellite image of Oyashirazu fishing port in Niigata Prefecture, Japan.

passed since the construction of the port breakwater at Santa Barbara, sandy beach downcoast of the breakwater has been well maintained.

In contrast, Oyashirazu fishing port in Niigata Prefecture, Japan, is one of the examples of the devastation of the downcoast coastline. Figure 8 shows a satellite image of this fishing port, where westward longshore sand transport of 3.7×10^4 m^3/yr was blocked by the fishing port breakwater, and sand deposited inside the port was dredged and removed, resulting in severe erosion downcoast of the fishing port owing to the deficit of sand and resulting in the entire coastline being protected by a seawall and concrete blocks (Uda, 1997). Because protection measures such as the construction of the seawall and the installation of concrete armor units were taken along the eroded coastline downcoast of the fishing port, which gradually expanded downcoast over time, an extensive area was altered by an artificial coastline comprising the seawall and concrete armor units. The construction of this fishing port began in 1966, and full-scale construction works started in early 1970. Therefore, 43 years have passed since. Even though the rate of longshore sand transport at Oyashirazu fishing port was lower than that at Santa Barbara by one order of magnitude, the coastline downcoast of the fishing port was rapidly covered with concrete facilities, i.e., natural sandy beach was altered in an artificially protected coastline.

Longshore sand transport at Pengambengan fishing port was estimated from the shoreline changes after the extension of the south breakwater in 2000. The previous shoreline before the extension of the south breakwater is approximately given by the broken line in Fig. 2, and the increase in foreshore area between 2000 and 2009 is 2.8×10^5 m^2. The volumetric changes of the beach can be calculated by multiplying the increase in foreshore area by the characteristic height of beach changes, h, which is defined as a regression coefficient between the change in the cross-sectional area of the beach and the shoreline changes. Using the relation $h_c = h_R/0.31$ and $h = 1.3h_c$ among the berm height h_R, the depth of closure h_c and h proposed by Uda (1997), and given the berm height of 1.2 m measured upcoast of the south breakwater, h becomes 5.1 m. Now, the sand volume deposited upcoast of the breakwater and the annual rate are calculated to be 1.4×10^5 m^3 and 1.6×10^5 m^3/yr, respectively. Assuming that the entire longshore transport was blocked by the south breakwater, longshore sand transport is estimated to be 1.6×10^5 m^3/yr. This transport rate has the same order of magnitude as 2.15×10^5 m^3/yr measured at Santa Barbara and is greater than the value of 3.7×10^4 m^3/yr evaluated at Oyashirazu fishing port.

At Pengambengan fishing port, a jetty had been extended at the tip of the south breakwater by May 30, 2014, as shown in Fig. 4, to block further sand deposition inside the port by a structural measure against sand deposition. However, sand was quickly deposited immediately south of the jetty owing to the blocking of the continuous longshore sand transport, suggesting further downcoast erosion. The past history clearly shows that soon after the sand deposition south of the jetty, sand will again be deposited inside the fishing port; a vicious cycle is occurring. If the construction of the breakwater will be continued in the same manner as in the present, it may lead the same situation as the eroded coast downcoast of Oyashirazu fishing port, where a large amount of expenditure was needed for the repair of the seawall. To avoid this situation, sand bypassing is a necessary measure, similarly to that at Santa

Barbara. Although Pengambengan fishing port is actively used as an unloading base of fishes, the cost of environmental protection will significantly increase in the long term, because sufficient measures have not been taken against beach erosion downcoast. The economic prosperity while leaving the outside economy poor will cause future problems. At a location 6.6 km northwest of the fishing port, downcoast erosion occurred with the elongation of a slender sand bar. Wooden fences have been used as a measure against erosion, even though they seemed to be ineffective. However, sand supply is possible after the tip of the sand bar connects with the opposite shore, which indeed had happened by May 30, 2014, as shown in Fig. 6. Taking this situation into account, it is better to maintain the beach by adopting the present simple measures, such as using wooden fences along with beach nourishment, if necessary, instead of constructing permanent structures against erosion.

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